AMPLITUDE MODULATION AND DEMODULATION OF CHAOTIC CARRIERS

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ABSTRACT

Amplitude modulation of broadband chaotic signals is introduced, similar to amplitude modulation of harmonic signal. Necessary conditions for modulation and demodulation of chaotic carrier are discussed. In particular, the type of chaotic carrier is discussed from the point of view of optimal demodulation. Estimates of demodulation accuracy are also presented.

INTRODUCTION

One of possible approaches to UWB communications is a so called direct chaotic communication (DCC) scheme [1–3], where a chaotic noise-like signal of microwave band plays the role of an information carrier. The use of chaotic carrier and chaotic oscillators as a chaotic source one allows to achieve some advantages in respect with conventional UWB communication schemes based on regular carriers, i.e. harmonic signals, ultra short pulses and so on.

DCC scheme means that generation, modulation and demodulation are performed in radio or microwave band. Until now the simplest digital modulation scheme of chaotic signal had been considered, where symbol “1” is represented by chaotic radio pulse at a prescribed position and symbol “0” by void position. Really this is a pulse modulation scheme and it is rather useful, for example, for high bit rate wireless applications (more than 100 Mbps), where transceiver must be as simple as possible. At the same time, for low bit rate communications the amplitude modulation (AM) of chaotic signal considered in this report is also rather interesting. From this point of view modulation used in DCC can be regarded as a special case of AM modulation of chaotic carrier.

AMPLITUDE MODULATION OF A CHAOTIC CARRIER

Let $x(t)$ be a passband signal, generated with some chaotic source, and let it occupy a frequency band $[F_1, F_2]$. Next, let’s introduce transformation of the chaotic signal $x(t)$, defined by

$$u(t) = m(t)x(t) , \tag{1}$$

where $m(t) = m_0 i(t)$ for AM with carrier suppression or $m(t) = m_0 i(t) + 1$ for AM without carrier suppression, m_0 be a constant, and $i(t)$ an information signal.

Further we will see that under appropriate conditions the signal $u(t)$ can be demodulated. This fact allows us to define transformation (1) as amplitude modulation of the chaotic carrier $x(t)$, similar to amplitude modulation of harmonic carrier. Consider the spectral properties of $u(t)$. Transformation (1) in frequency band yields the following convolution $U(f) = M(f) \otimes X(f)$, where $U(f)$, $M(f)$ and $X(f)$ are Fourier transforms of the signals $u(t)$, $m(t)$ and $x(t)$, respectively.

Since the spectrum $X(f)$ of the chaotic signal $x(t)$ occupies frequency band $[-F_2, -F_1]$U$[F_1, F_2]$ (see Fig. 1) and the spectrum $M(f)$ of signal $m(t)$ occupies frequency band $[-W, W]$, the spectrum $U(f)$ of the signal $u(t)$ occupies the frequency band $[-F_2-W, -F_1+W]$U$[F_1-W, F_2+W]$ and the width ΔF of positive band $[F_1-W, F_2+W]$ is $\Delta F = (F_2 - F_1) + 2W$. In particular, it means that, lower frequency of modulated carrier must be higher than higher frequency of information signal, i.e. $W < F_1$. Further we will consider the spectrum properties only for positive frequencies.

DEMODULATION OF THE AMPLITUDE MODULATED CHAOTIC CARRIER

Let us evaluate a possibility of recovering information from the amplitude-modulated chaotic signal. First, consider the case, when the receiver possesses an exact copy of the chaotic carrier generated in the transmitter. By analogy with a coherent receiver for amplitude modulated harmonic carrier, let us introduce a coherent receiver for amplitude modulated chaotic signal. This receiver consists of a multiplier and a low-pass filter (LPF) with the cut-off frequency W equal to the baseband width of some modulation signal $m(t) = m_0 i(t)$ (see Fig. 2a).

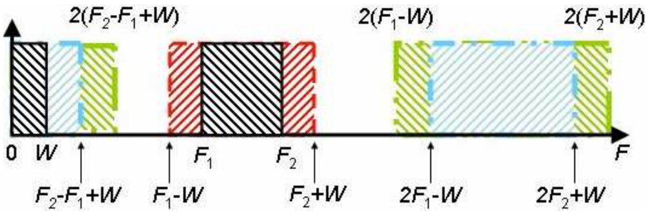

Fig. 1. Frequency bands: information signal $i(t)$ and chaotic carrier $x(t)$ (black solid); modulated carrier $u(t)$ (red dash); coherent demodulated carrier $v(t)$ (blue dash-dot); non-coherent demodulated carrier $v''(t)$ (green dash-dot-dot).

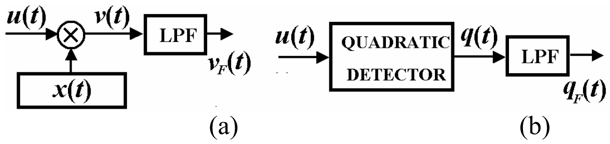

Fig. 2. Receivers for AM chaotic signals: (a) – coherent receiver; (b) – non-coherent receiver.

The multiplier performs multiplication of the modulated chaotic signal $u(t)$ by a copy of the chaotic signal $x(t)$, generated in the transmitter. The signal at the output of the multiplier is

$$v(t) = m(t)x^2(t) = Am_0 i(t) + m_0 i(t) y_b(t) + m_0 i(t) y_p(t)\,, \tag{2}$$

where $x^2(t)$ can be represented as $x^2(t) = A + y_b(t) + y_p(t)$, A is a constant, $m_0 i(t) y_b(t)$ occupies the frequency band [0, F_2–F_1+W] and $m_0 i(t) y_p(t)$ occupies the frequency band [$2F_1$–W, $2F_2$+W]. Representation (2) is the result of convolution of spectrums of $u(t)$ and $x(t)$ (see Fig. 1). First term in (2) is the useful signal, the second is low-frequency disturbance, and third is a high-frequency disturbance that can be completely suppressed by low-pass filter. LPF also partially removes the low-frequency disturbance.

A possible structure of non-coherent demodulator of chaotic signal is depicted in Fig. 2b and its structure is similar to the non-coherent demodulator of harmonic carrier. Demodulator consists of an envelope detector (quadratic) and a lowpass filter. The quadratic detector output is

$$q(t) = (1 + m_0 i(t))^2 x^2(t) = A + 2Am_0 i(t) + Am_0^2 i^2(t) + [1 + 2m_0 i(t) + m_0^2 i^2(t)]y_b(t) + [1 + 2m_0 i(t) + m_0^2 i^2(t)]y_p(t) \tag{3}$$

where A, $y_b(t)$, $y_p(t)$ are the same as in (2). We can see from (3) that similar to the non-coherent receiver of amplitude modulated harmonic carrier, the modulation without suppression of carrier must be used to have the term containing $i(t)$. The last term occupies high-frequency band $[2F_1 - 2W,\ \ 2F_2 + 2W]$, so to remove it the cut-off frequency of lowpass filter must be less than $2F_1 - 2W$, i.e. $W < 2F_1 - 2W$ or $W < (2/3)F_1$. Again as for coherent demodulation the third and fourth terms in (4) are low-frequency disturbance whose frequency band partially overlaps the frequency band of information signal $i(t)$.

TYPES OF CHAOTIC CARRIERS

As is shown above disturbance due to non-coherent receiving cannot be eliminated completely by filtering, so it corrupts information signal at the detector output. However, appropriate choice of chaotic carrier parameters can reduce the level of disturbance. Here we will consider the phase-chaotic signal as a carrier, and we will show that disturbance can be rather low for such type of carrier.

Chaotic signal $x(t)$ as any other signal can be represented in the following way $x(t) = a(t)\cos(\phi(t))$, where $a(t)$ and $\phi(t)$ are some signals. This representation allows to stress differences in types of chaotic signals. Namely, let us define a signal with variable $a(t)$ and $\phi(t)$ as amplitude-chaotic, but a signal with constant amplitude $a = const$ and variable $\phi(t)$ as phase-chaotic one.

Both for coherent and for non-coherent receivers, the signal fed to the lowpass filter contains terms with $x^2(t)$. If the amplitude-chaotic signal is considered, then $x^2(t) = a^2(t)\cos^2(\phi(t)) = a^2(t)[1+\cos(2\phi(t))]/2$ and the term $a^2(t)$ will always fall into the lowpass filter band and will disturb useful signal $i(t)$. But the use of phase-chaotic carrier yields $x^2(t) = a[1+\cos(2\phi(t))]/2$ and disturbance due to terms containing $x^2(t)$ will be completely suppressed by LPF.

Phase-chaotic signal can be generated by PLL [5] and it is represented as $x(t) = \cos(2\pi f_0 t + \alpha\varphi(t))$, where f_0 is the center of frequency band of $x(t)$, $\varphi(t)$ is a chaotic signal produced by a chaotic source, α is a constant. It can be seen that the larger α the larger spectrum spreading of $x(t)$. Otherwise, with decreasing α the spectrum of $x(t)$ becomes narrower and $x(t)$ tends to harmonic signal for $\alpha \Rightarrow 0$.

COHERENT AND NON-COHERENT DEMODULATION OF PHASE-CHAOTIC CARRIER

Let for fixed α the spectrum of phase-chaotic carrier $x(t)$ occupy the band $[F_1, F_2]$. Coherent receiver yields (see (2)) $v(t) = m(t)x^2(t) = m(t)[1+\cos(4\pi f_0 + 2\alpha\varphi(t))]/2$ and $A = 0.5$, $y_b(t) = 0$, $y_p(t) = 0.5\cos(4\pi f_0 + 2\alpha\varphi(t))$. So, it is possible to recover information (modulating) signal without disturbances by using proper lowpass filter.

The same situation takes place for non-coherent demodulation since low-frequency disturbance is zero $y_b(t)=0$. High-frequency disturbance $y_p(t)$ can be completely removed by low-pass filter. So, at the lowpass filter output we have the signal that is proportional to $q_F(t) = A(1+2m_0 i(t) + m_0{}^2 i^2(t))$, i.e. to the the signal with the same structure as for conventional non-coherent detector of narrow-band carriers.

Consequently, the phase chaotic carrier can be theoretically regarded as the optimal carrier for AM among all the chaotic carriers involved.

NUMERICAL SIMULATION

Numerical simulation for phase chaotic carrier has been carried out to evaluate the quality of the recovered information signal in the receiver. The modulating (information) signal is lowpass. Both coherent and non-coherent receivers are considered. For evaluation of signal quality we introduce the signal to disturbance ratio (S/D) defined by $S/D = 10\lg(P_s/P_d)$, where P_s is the power of information signal $i(t)$, P_d is the power of the difference between original information signal $i(t)$ and the evaluated signal $v_F(t)$ or $q_F(t)$ at the receiver output. All frequencies were scaled to 1 (Nyquist frequency). Numerical simulation consists of two stages.

At the first stage, the double sideband modulation of phase-chaotic carrier with coherent receiver was investigated. Influence of information signal bandwidth W and parameters of phase-chaotic carrier on quality of demodulated signal were analyzed. Spectra of information signal, chaotic carrier and modulated chaotic carrier and corresponding waveforms are depicted in Fig. 3. It was shown that when frequency bands corresponding to the modulating signal and the chaotic carrier do not overlap, i.e. when condition $W < (2/3)F_1$ is fulfilled, the quality of demodulated signal is rather high (S/D =~ 60 dB). If condition $W < (2/3)F_1$ is broken the quality of demodulated signal is rather low (S/D =~ 15 dB).

At the second stage the double sideband modulation with non-coherent receiver was investigated for different modulation depth m_0 and bandwidth W, F_1, F_2. Simulation results of the quality of demodulated signal as a function of modulator parameters are depicted in Fig. 4, where the S/D vs bandwidth W for different modulation depth m_0 is plotted. One can see that disturbance of demodulated signal decreases with decreasing modulation depth. This fact qualitatively agrees with above mention expression for $q_F(t)$ that also points at increasing quality of demodulated signal with decreasing modulation depth. However, it is necessary to take into account that the presence of noise does not allow to make the value of modulation depth arbitrarily small because it yields increase of noise power at the output of the receiver, so the compromise value of modulation depth must be chosen.

CONCLUSIONS

The method of amplitude modulation of broadband chaotic carrier is proposed. It was shown that quality of demodulated signal depends on parameters of modulation-demodulation scheme and on type of chaotic carrier. In particular the use of phase-chaotic signal and coherent receiver gives rather high quality of demodulated signal. This fact allows us to conclude about potential applicability of amplitude modulation of chaotic carrier for direct chaotic communication systems.

ACKNOWLEDGMENTS

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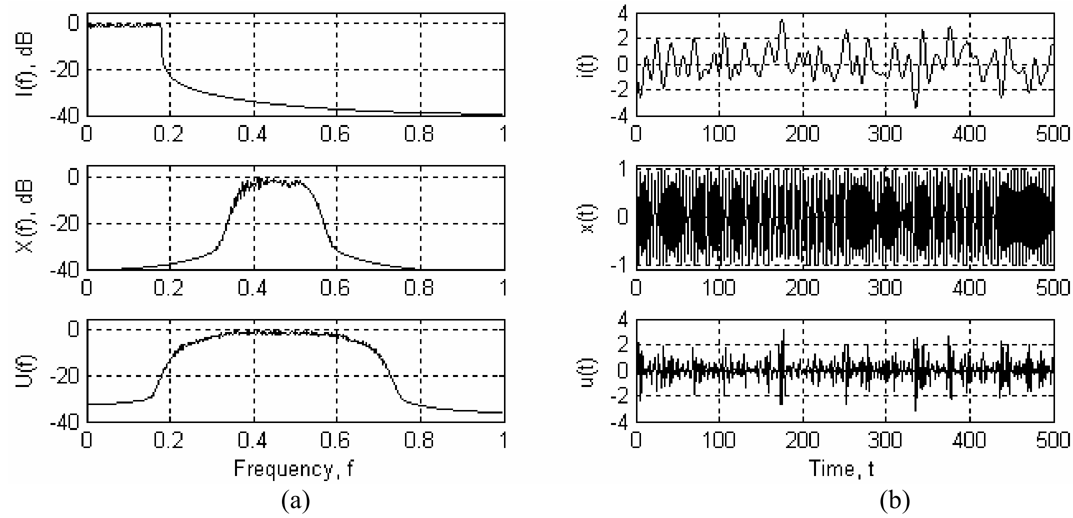

Fig. 3. Simulation results for phase-chaotic carrier and coherent demodulation: (a) – spectrums of information *I(f)*, phase-chaotic *X(f)*; modulated phase-chaotic *U(f)* signals and their waveforms (b), respectively. W=0.18, F_1=0.33, F_2=0.53, *S/D* =~ 60 dB.

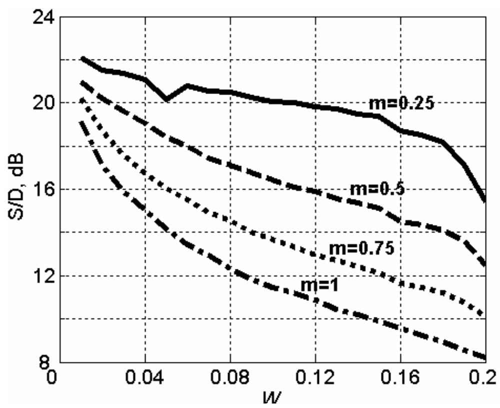

Fig. 4. Simulation results for phase-chaotic carrier and non-coherent demodulation: *S/D* ratio vs modulation depth m_0 and information signal bandwidth W. F_1=0.33, F_2=0.53.